Special Issue: Planetary Diversity

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Planetary Diversity

Planets come in a wide variety of types and exhibit a wide range of complex behavior. Still, we can ask—and answer—some fundamental questions about them.

David J. Stevenson, Guest Editor

Once upon a time, on a planet far away, a guest editor for the local equivalent of PHYSICS TODAY *was puzzling over the challenge of an issue devoted to planetary science. For it seemed to her that planets are so common yet so diverse in character that, even omitting planetary biology, one could not hope to cover their richness and accompanying scientific challenges. Should one talk about the recently discovered planets with neon oceans, or the purely iron planets, stripped of their primordial rocky mantles? Or the systems whose disks are continuously recycled so that their planets keep falling into the central star, only to be replaced by copies in the outer suburbs? What of those systems where biology has consumed all the planetary matter because there are a very large number of small planets? (Such systems optimize entropy production because they maximize the interception of light from the central star.) Or the planets composed of giant single quantum states?*

From her vantage point on an ice-covered world orbiting a giant planet that fills much of the spectacular night sky, she thought back to the time when scientists had only to be concerned with their planetary neighbors and the indirect evidence of planets around other stars. Science then had seemed simpler, a mere generalization of the concepts that governed the homeland. The diversity presented by stellar and galactic astronomy had seemed so great because one had not yet fully recognized the diversity of planets. [Fade to black. . . .]

Much of the universe is unknown still, at least to us on Earth, although most of the known baryonic mass is evidently in a simple form. Most of it is hydrogen-dominated gas or plasma, simple in behavior though bearing the seeds of elemental diversity through thermonuclear reactions in stars. The predominance of hydrogen and the simplicity of its material properties allow astronomers to collapse most of the behavior of stars into a two-dimensional plot, the Hertzsprung–Russell (H–R) diagram of color versus brightness. And most stars fall along the main sequence of that diagram. Even the degenerate stars—the white dwarfs and neutron stars—are simple, though in a different way because so much of their matter exists in an ideal extreme form (as a Fermi gas). Only neutron stars compete with planets for the phenomenological richness and complexity of their behaviors.

That richness arises from imperfection and from chemistry, here broadly defined to embrace the range of behaviors that can occur when materials are alloys or physical mixtures. Planets lack the equivalent of the low-dimensional H–R diagram because of their complexity. But the richness of planets also arises from their choreography—that is, the remarkable range of patterns in which they form and interact. And, of course, life exists on planets, though we do not yet know at what frequency.

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What is a planet?

This question must be asked, even if only to explain why it is unimportant. Planetary scientists study what is in orbit around stars but not doing what a star does (or used to do in an earlier life), which is fusion. All scientific labeling is secondary to the essence of science, and labels such as "planet" exist only to help us talk to each other. Dust, asteroid belts, and cometary belts or clouds are just as important in the grand scheme of things. Mike Brown's article on page 49 concerns some of the new things we are learning about such objects. But for purposes of this discussion, a planet could be anything from the range of about $1/10$ the mass of Earth's Moon to about 10 Jupiter masses. That is a range of almost six orders of magnitude in mass. On the low mass end, the range extends roughly to a point at which the effects of gravity and insulation allow the inside of a body to be different from the outside. (Even that is a rather arbitrary distinction, because the inside of a comet or asteroid can differ from its outside). The high mass end extends roughly to a point at which the fusion process is possible from the deuterium in a hydrogen-dominated body.

Within that range, a break in the spectrum of masses occurs among those objects found so far in orbit around main sequence stars.[1] Scientists have discovered many more planets with masses below 10 Jupiter masses than they have planets in the brown dwarf range—from 10 to 70 or 80 Jupiter masses (see figure 1). The lowest mass for sustained fusion of light hydrogen is roughly 80 Jupiter masses.

Why do planets exist?

On one level, this is an easy question to answer. Planets exist because of angular momentum. When a star forms from the interstellar medium, the collapsing cloud of gas and dust has unavoidable vorticity, far too great to be accommodated in the hydrostatic star that gravity tries to make from the available mass. The excess angular momentum can be accommodated by fragmenting the cloud, a process that leads to a binary or multiple-star system. But, in general, even those fragments will have too much angular momentum and must each form a disk and a central stellar concentration of mass. From those Keplerian disks, planets form.

Angular momentum does not guarantee planets, though. Gas giants can form in a manner somewhat analogous to

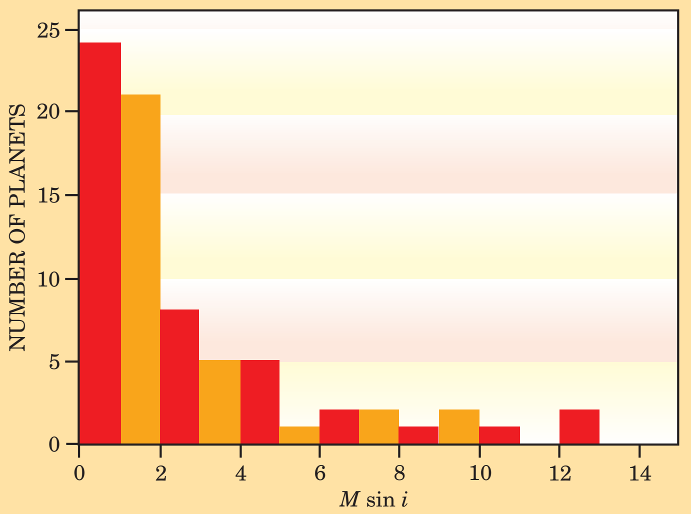

Figure 1. The spectrum of masses among the extrasolar planets found so far exhibits a break close to 13 Jupiter masses. Among the 75 planets plotted here, the distribution peaks at low mass even though such planets are the hardest to find. To detect and measure the extrasolar planetary masses, scientists look for a Doppler shift in the spectral lines from the atmosphere of stars. The method yields $M \sin i$, in which M is the mass (scaled to Jupiter) and i is the angle between the orbital plane normal and Earth's line of sight. (Courtesy of Geoff Marcy.)

stars by a gravitational instability of the gas disk, provided it is sufficiently cold and dense. No one knows whether that mechanism actually works and played a significant role in our solar system or other planetary systems. The more popular view continues to be that planets like Jupiter form through nucleation—the formation of a solid body followed by gas inflow onto that body.

Solid bodies undoubtedly formed, but there is no consensus on this process either. Late stages in the growth of big objects were surely dominated by gravity. However, the relative importance of sticking (that is, weak chemical forces) and gravity is uncertain for bodies just a few kilometers in size. The lack of consensus comes not so much from ignorance of process as from the complex interplay of time scales and rates. One suspects that different planetary systems will have different outcomes, probably including the case in which material fails to accumulate into big bodies. In her article on page 56, Robin Canup discusses our current understanding of planet formation.

What determines diversity?

When we consider what exists and what is possible, three issues are paramount: stability, cosmochemistry, and origin. Stability prompts the question, Is the body able to survive a long time—say, billions of years? Cosmochemistry prompts the question, Is the body's composition plausible, given the starting materials that the universe provides? Origin prompts the question, Is there a dynamical pathway that can make such a body? These three factors are strong, moderate, and weak, respectively, in their power to constrain the formation of possible planets.

Stability considerations exclude a wide range of objects or characteristics that cannot persist. For example, a self-gravitating one-Earth-mass body of hydrogen and helium with the entropy of Jupiter could not exist in Earth's orbit. It would literally disassemble by tidal action and the action of external UV radiation. Somewhat less dramatically, stability considerations also preclude small bodies close to the parent star from retaining substantial atmospheres. Stability should be regarded as a strong constraint on hypothetical planets because the physical considerations are firmly based and well understood. Of course, it is usually much easier to prove that something is unstable than to prove it stable, so even this consideration has its limitations.

Cosmochemistry is the legacy of thermonuclear synthesis. It varies with cosmological epoch and locality, but the broad consequences are invariant. The elements can be divided into three classes on the basis of nuclear physics and physical chemistry: gases, ices, and rocks (see figure 2). Gas refers primarily to hydrogen and helium, the most abundant elements in the universe. These elements also happen to comprise molecules that do not condense as solids or liquids under conditions that are encountered during planet formation. The material deep within a planet such as Jupiter can be called a liquid metal but it has a much higher entropy than the value at the conventional critical point of molecular hydrogen, where liquid and gas merge. Tristan Guillot discusses our current understanding of the giant planets in his article on page 63.

Ice refers to the compounds that form from the next most abundant elements: oxygen, carbon, and nitrogen. These compounds are primarily hydrides (water, methane, and ammonia) but also include carbon monoxide, carbon dioxide, and molecular nitrogen, among others. The ice label does not mean that the constituents are necessarily found as solid materials, although that is indeed the form in which they would provide the building blocks for planets. However, condensation requires low temperatures, corresponding to the orbit of Jupiter and beyond in our solar system. Ice is roughly two orders of magnitude less abundant than gas, by mass.

Rock refers to everything else—primarily magnesium, silicon, and iron, and the oxygen that would naturally combine with those elements. Rock is less abundant than ice even though it includes most of the periodic table. Remarkably, nuclear physics orders the elements according to abundance in a way that also naturally groups the elements into chemical classes.

Such elementary considerations enable us to understand why a Jupiter-mass planet made mostly of iron, say, would probably not exist. Typically, insufficient iron would be around during the formation of a planetary system for scientists to imagine that happening. Our inclination to interpret Jupiter-mass extrasolar planets as gas balls (even without information on the size or composition) is not mere Solar System prejudice, but is guided by cosmochemical principles. Likewise, we could explain the known properties of Earth's core by an alloy of niobium but choose not to do so because a much more abundant element—iron—can do the job.

On the other hand, we have learned to be suspicious of arguments that relate expected planet composition to location. Although it is tempting to argue that planets forming close to stars might tend to have a composition dominated by materials that condense at high temperature, we probably cannot exclude formation of gas balls at small radii. Orbital migration cannot be overlooked as an important process in the structure of many planetary sys-

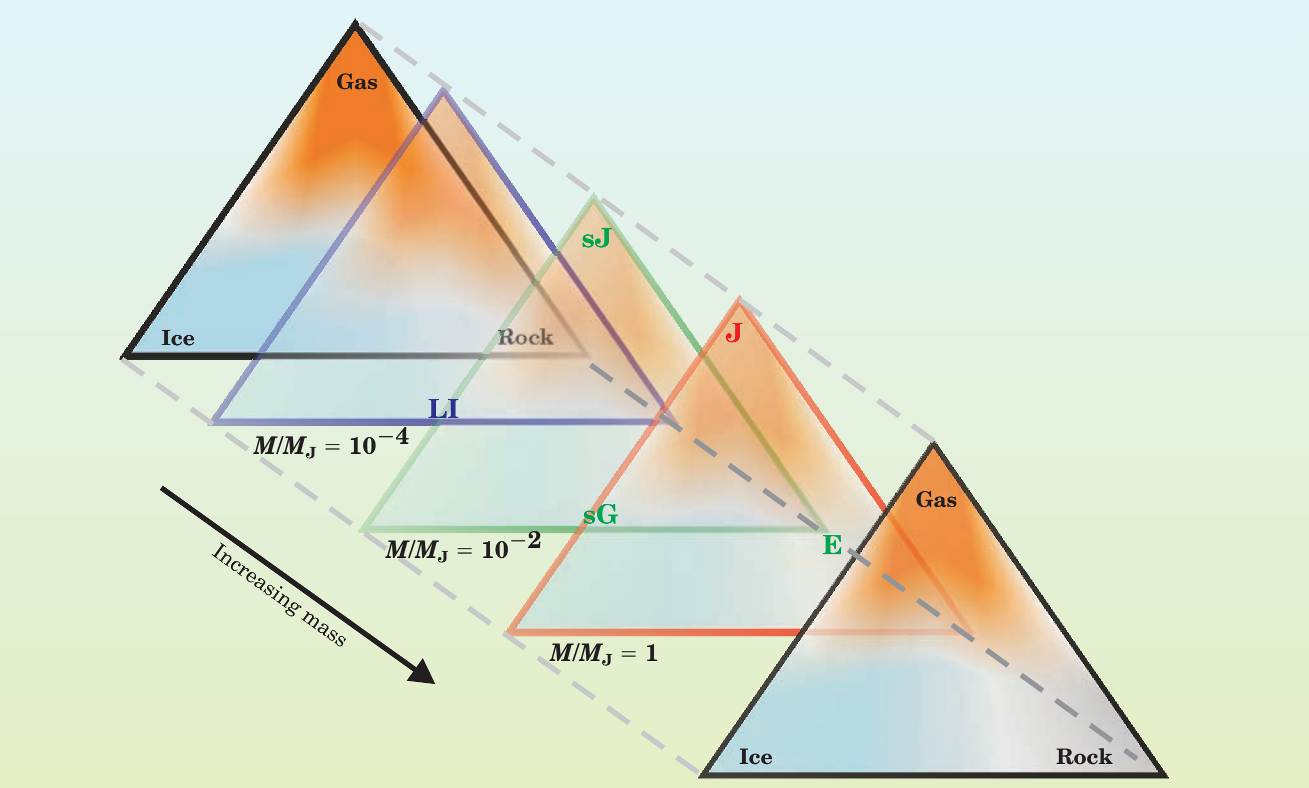

Figure 2. This prism encompasses all possible planets in the universe. Gas, ice, and rock define each vertex of the prism, and the third dimension is mass in units of M_J, the mass of Jupiter (J). E refers to Earth, and LI to large icy satellites such as Ganymede. Two other classes of bodies are not found in our solar system: sub-Jupiters (sJ), bodies like Jupiter but much less massive and super-Ganymedes (sG), bodies like Ganymede but much more massive.

tems, probably including most of those extrasolar systems discovered so far. Orbital migration arises through an exchange of angular momentum between a massive gaseous disk and an embedded giant planet and can cause a large change in the planet's orbit in only 100 000 years. The presence of water on Earth and heavy noble gas excesses in Jupiter also cause us to question whether all the material in planets condensed near their current orbit. Much of Earth's water was probably delivered from the Jupiter zone or beyond. Thus cosmochemistry, although helpful, is only a moderate constraint on what exists, because materials can end up in different places from where they first accumulated.

Origin scenarios lead one to "explain" particular outcomes. The test of a good theorist is the ability to explain any outcome, even when the data are wrong. This irony highlights a fundamental difficulty in explaining how things came to be: The basic physics—dynamics of many-body systems interacting through gravity—is better understood than most things in planetary science. But that does not mean one can severely limit the possible outcomes of an event! There are too many contingencies to account for, and the outcome of an event may depend on a particular sequence of processes with different (but variable) time scales. An example of a crucial time-scale issue is the timing required for the loss of nebular gas; that is, the time at which most of the hydrogen and helium that is not grabbed by the giant planets or the Sun is sent back into the interstellar medium. The outcome for a particular planetary system might be wildly different if the nebular gas is expelled sooner or later than in our system. Even for a particular ordering of major events, the outcome still depends on chance, in the sense of a deterministically chaotic system.

The problem is reminiscent of a current debate in biological evolution between those who argue that Darwinian natural selection on Earth can lead to an extraordinary range of possible outcomes sensitive to contingencies[2] and those who say that the range of outcomes is quite narrowly limited.[3] In the debate over biology, just as over planetary formation, scientists agree about underlying process—most believe Darwin was essentially correct—yet much room exists for disagreement about consequence.

Irrespective of who is right about life on Earth and elsewhere, it seems likely that the universe of planetary systems will, like Darwinian evolution, seek out all ecological niches and exhibit a remarkably wide range of patterns, even while conforming to the physics and chemistry exhibited in our neighborhood. For that reason, origin scenarios can probably only weakly constrain the evolution of planets.

How unique is our solar system?

The current observational evidence of extrasolar planets certainly contains many instances that are markedly different from our solar system.[1] That finding is possibly an observational bias: Systems with giant planets in orbits with periods less than a year are much easier to discover than systems like our own, especially using the currently dominant technique based on the Doppler shift of light from the parent star. This unexpected outcome is apparently quite common, occurring for roughly 10% of nearby Sunlike stars.[1]

The most likely reason that giant planets exist in

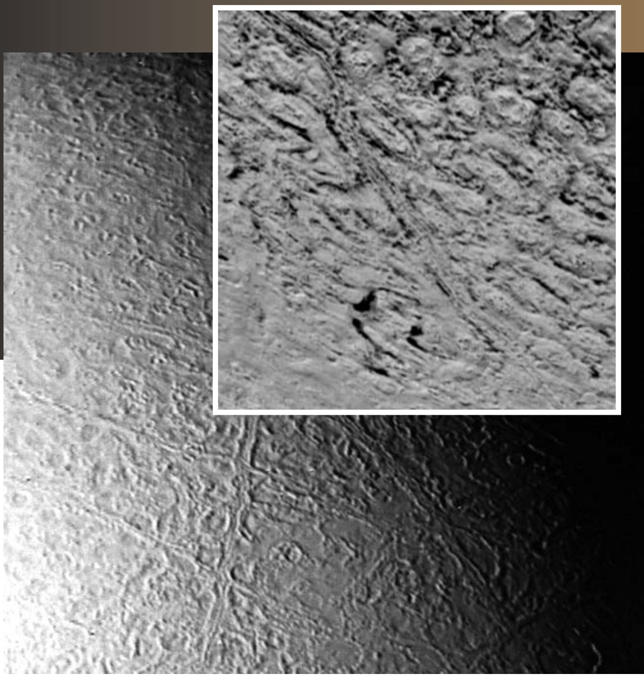

Figure 3. Triton is a planetary moon that orbits Neptune. This picture and its inset, taken by *Voyager 2* in 1989 from 80 000 and 25 000 miles, respectively, show an icy surface scarred by enormous cracks. Triton's planetary evolution is still poorly understood, and the surface deformation may be a testament to the role of planetary processes even on bodies that are less massive than Earth's Moon. (Courtesy of JPL/NASA.)

near-star orbits is that they migrated there from much more distant locations, where they first formed. The transfer of angular momentum between a planet and the more massive gas disk in which it sits—and which accounts for the migration—is well understood in principle. Still, many aspects of the phenomenon remain mysterious. In particular, scientists don't know why or whether our solar system avoided this process. A giant planet sweeping through the natural zone of terrestrial planet formation might exclude the formation of planets like Earth. Does that mean Earth is uncommon, or merely that we have not yet found its analogs? We expect to answer that question in the next decade or two.

What has our solar system taught us?

In the past 40 years, planetary science has evolved from a minor branch of astronomy to an activity that embraces all the physical sciences and part of biological science. Planetary science is not a scientific discipline in the usual sense of being a specialty field; it is rather an interdisciplinary combination of many areas of science. The successful exploration of space, primarily by unmanned spacecraft, has been central. Remote spacecraft have visited all of the planets in our solar system now except Pluto (and any other more distant objects that might meet my definition of a planet). Several lessons have emerged from the maturing of planetary science.[4]

Common processes are at work. When remote spacecraft visit other planets for the first time, researchers are almost always initially surprised by what they find. Examples include the magnetic field of Mercury; the high argon-36 content (relative to Earth) of the Venus atmosphere; Mars features created by water flow; the remarkable difference in appearance of Ganymede and Callisto, two of Jupiter's moons; and the strength of the winds on Saturn. Yet the underlying physical and chemical processes of these places are not bizarre; their terrestrial analogs are right under our noses. Ice caps form, winds blow, volcanoes erupt, and magnetic fields are produced here on Earth and elsewhere in the Solar System. Far-flung explorations to other planets and moons test our imagination and challenge basic scientific understanding, but they ultimately confirm our grasp of the basic physics and chemistry and expand the knowledge base about the physical universe. Mars has a mass that is 1/10 that of Earth, but it has volcanic structures similar to oceanic island volcanoes on Earth—in Hawaii, for example. Mars also has sand dunes, valley structures similar to those found in Earth's arid polar regions, and water-ice polar caps. Bruce Jakosky and Michael Mellon's article on page 71 discusses some current understanding of Mars, especially the role of water.

Common processes yield diverse outcomes. Mass, compositional class (rock, ice, or gas), and distance from the Sun are not sufficient to characterize planetary behavior. There are too many degrees of freedom, some of which seem minor yet prove to be major. Consider the role of water in terrestrial planets. Earth's water profoundly affects global dynamics. For one, it softens mantle rocks, thereby preparing the way for an asthenosphere—the soft layer underlying the plates. Its presence is also quite likely a pivotal condition for plate tectonics, which in turn partly determines the cycle of water: When plates subduct, water is carried into Earth's interior. Had Earth started out differently—with a modest amount of more or less water, say—the planet might have evolved quite differently. And perhaps the major reason Venus is unlike Earth is because it lacks water in its upper mantle. That could at least partly account for the absence of plate tectonics there.

Consider also the role of sulfur, another minor constituent of the Earthlike planets (Mercury, Venus, Earth, and Mars). Sulfur is iron-loving, so it likes to reside in the iron core of a planet. It's also an antifreeze, so a planetary core with lots of sulfur is less likely to fully solidify. A core that only partly solidifies yields a buoyant fluid and keeps energy available to sustain the internal motions required to generate a magnetic field. Two otherwise identical planets with only modest differences in the sulfur concentrations of their cores, therefore, could differ dramatically: One might have a magnetic field and the other might not. Ganymede and Callisto have ended up remarkably different, even though they are similar in size and bulk composition. The article by Torrence Johnson on page 77 discusses the remarkable diversity of the Galilean satellites, the first planetary system discovered other than our own.

Planets must be understood in context. It is not enough to think about planets in isolation. The influence of the Sun and Moon on Earth is as clear as daylight and tides, but subtler external factors also influence the history and evolution of a planet. A massive impact at the end of the Cretaceous period on Earth—an event once controversial but now widely accepted—is a likely cause of the extinction of many species, dinosaurs among them. Almost certainly, impacts were important in establishing the early environments on Earth and Mars and thereby significant in abetting or hindering the conditions necessary for life. Jupiter, too, may have been an unwitting nurturer of life on Earth by restricting the number of impacting bodies that reached it. Small disturbances of Earth's orbit and orientation, for example, help determine fluctuations in Earth's climate, including the coming and going of ice ages. The same probably holds true for Mars.

A historical perspective is important. A major goal of planetary science is to understand how things came to be. Astronomers may look at large redshifts for clues to ancient events that occurred far away, but planetary scientists trying to understand the Solar System look to clues in the rocks and morphological forms on solid planets. This geological approach embraces the idea that we can read history in the solid bodies around us because they sometimes retain a memory. The precise dating of meteorites has revealed an early, relatively brief period of activity, including melting, in many of the Solar System's small, solid bodies. The uniformity of those dates is one line of evidence enabling us to estimate the age of the Solar System (now believed to be about 4.6 billion years). The oldest rocks on the Moon are almost as old as the Solar System itself, a fact that attests to the rapidity of some planetary processes.

Planetary scientists cannot yet operate like field geologists. Even the Apollo astronauts were greatly limited in their investigations. The technical challenges of getting to and studying Mars mean it may be a long time before a true stratigraphy can be constructed for the various regions of that planet. Still, there are ways to tease out history. On Venus, for example, the paucity of impact craters suggests that the outermost layers have been recycled over the past billion years. Of course, the apparent lack of any current process capable of such recycling will need to be reconciled with the inference. Perhaps Venus once had plate tectonics but no longer does. On Mars, the younger-appearing northern terrains may indicate an early recycling, possibly suggesting a more ancient epoch marked by plate tectonics. On Triton, Neptune's large moon, the low crater density indicates that resurfacing is at work. That could mean that Triton may have an active interior, remarkable for a body so small (see figure 3).

Earth-based data, lab work, and theory are still essential. It is easy to be impressed by the data returned from spacecraft. It is easier to forget that much of what we learn about planets comes from Earth-based activities, either as independent efforts or as complements to spacecraft-based activities. Some of that planetary knowledge comes from using large telescopes, but much of it is small science—bench-top experiments on the properties of materials and computer simulations of the formation of planets and moons, for instance. The science return per dollar invested in ground-based work is very high. The research has led to key discoveries and significant information: the existence of Jupiter's large magnetic field; the rotation states of Venus and Mercury; the strong green-

Figure 4. The *Huygens* probe will drop into the dense, smoggy atmosphere of Titan in January 2005 after the current *Cassini* mission reaches Saturn. Part of the surface may be lakes or oceans of methane, ethane, and other hydrocarbons, and part may be outcrops of "bedrock" water ice. Although the actual splashdown site is planned for the side of Titan where Saturn is not visible, this artistic impression is somewhat realistic and based on current knowledge, including a possible inclination and faint appearance of Saturn for a near-equatorial view on Titan. The atmosphere might not seem as transparent to the human eye as rendered here, but is transparent at some near-infrared wavelengths. (Courtesy of Mark Robertson-Tessi and Ralph Lorenz.)

house effect and clouds on Venus; the diversity of shapes, rotation states, and compositions of asteroids; the strange surface of Titan; and the persistence and high temperatures of volcanism on Io, Jupiter's innermost moon. Furthermore, confidently interpreting spectra to learn about the compositions of other atmospheres or interpreting planetary compositions and behavior from condensed matter physics is only possible with laboratory data for comparison.

An interdisciplinary approach works best. Outsiders sometimes perceive the resulting science as lacking the detail and precision apparent in each contributing discipline. Consequently, scientists must rely heavily on physical reasoning, inferential arguments, and modeling to interpret land forms whose natures are particularly difficult to discern without more detailed information. But computational studies have emerged over the past few decades as a widely used third branch of scientific investigation that complements the traditional pair of experiment and theory. A great bonus comes with this broader approach: Planetary scientists have become indispensable players in the quest to answer fascinating questions that would fall outside a more narrowly focused discipline. Research in many aspects of Earth's evolution and behavior requires a planetary perspective, for example. And one of the grandest scientific mysteries of all—the origin of life—is unlikely to be solved only by biologists, physicists, and chemists. That achievement is sure to require the mindset of planetary scientists as well.

Challenges for the future

Planetary science is evolving into a field with rich interplay between the traditional area of geoscientific approaches applied to planets and the new areas of extrasolar planets and exobiology. Astronomers provide the techniques to study other planetary systems, but planetary science provides the intellectual framework for building a story from what we will learn, especially as we get compositional spectroscopic data and perhaps detect Earthlike planets[5] in the coming decades. In the nearer term, the exciting investigation of our own Solar System continues. Figure 4 illustrates one aspect of a very significant upcoming event, the arrival of the *Cassini* mission at the Saturn system in a few months. The greatest scientific question of all, the presence and prevalence of life elsewhere, remains a tremendous motivator despite the uncertainty of success.

Physics students and professionals sometimes express concerns about the future of physics. Sidney Nagel's opinion piece (see PHYSICS TODAY, September 2002, page 55, and reader responses in the January 2003 issue, page 12) exemplifies the feeling among some scientists that physics might have a problem as a chosen area for exciting research. Planetary science is among the fields of physics that do not suffer from a dearth of challenges and opportunity. Too few highly talented physics-trained people are entering planetary science. If you have read this far, then take action! Consider this area for yourself or suggest it to talented students. And enjoy the articles that follow.

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